Non-thermal emission and magnetic fields in nearby galaxies

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Chapter 6

Conclusions

6.1 Summary of key results

In this PhD thesis, we have investigated the low-frequency radio continuum properties of a sample of nearby dwarf and normal late-type spiral galaxies. For this work, we observed two normal late-type spiral galaxies (NGC 4258 and NGC 5457) and four starburst dwarf galaxies (NGC 1569, NGC 4214, NGC 2366, and DDO 50) using the LOw Frequency ARray (LOFAR) with complementary 1.4 GHz observations with the Westerbork Synthesis Radio Telescope (WSRT). We summarise our main results below:

In **chapter 2**, we studied the radio continuum properties of the star-forming disk and the anomalous arms in the nearby spiral galaxy NGC 4258 using new radio continuum observations with LOFAR and the WSRT radio telescopes. Using the new sensitive radio images of NGC 4258 at 150 MHz and 1400 MHz, we were able to trace weak radio continuum emission from the star-forming disk up to a distance of 20.73 kpc from its center. Using the new radio images, we have also determined for the first time the equipartition magnetic field strength in the disk of NGC 4258 which peaks at about 20 μG in the inner disk and decreases to 4 μG about 20 kpc away from the nucleus.

The 3-dimensional orientation of the anomalous arms in NGC 4258 with respect to its star-forming disk has been a mystery since the discovery of the anomalous arms in 1961. In **chapter 2**, we have shown that radio polarimetry data can be used to help resolve this long-standing question. Our 1.4 GHz radio polarimetry data, complemented by H I and Hα images of NGC 4258, suggest that the anomalous arms have a hybrid morphology where the inner parts of the arms are embedded in the disk while the outer parts of one of the arm (the eastern arm) is located out of the plane, on the near side to the observer.

In **chapter 3**, we presented a multi-frequency radio continuum study of the nearby spiral galaxy M 101 using data from the LOFAR and the WSRT radio telescopes. In this chapter, we have demonstrated that diffuse radio continuum emission on arcmin-scales can be recovered at 150 MHz after applying an advanced facet-based direction-dependent calibration and imaging techniques.

From the LOFAR and WSRT radio images of M 101 in the frequency range spanning from 146 MHz to 2270 MHz, we see that the angular extent of the radio continuum disk increases with decreasing frequency. The observed steepening in the slope of the radial brightness distribution and the steepening of the azimuthally averaged non-thermal spectral index profile suggest that the radio emission arising from the outer parts of the galactic disk, which are most prominent at low radio frequencies, are dominated by an old population of cosmic rays.

The high angular resolution radio images of M 101 presented in this thesis allowed us to demonstrate that the integrated flux density values of M 101 reported in the literature are all biased by confusing background radio sources. The integrated radio spectral energy distribution – corrected for confusing radio sources – shows spectral flattening towards low radio frequencies which we attribute to free-free absorption.

In **chapter 4**, we studied a sample of four bright, nearby dwarf galaxies (NGC 1569, NGC 4214, NGC 2366, and DDO 50) which were selected based on their particularly high radio brightness. Of the four dwarf galaxies studied, extended diffuse emission was detected in only two of these galaxies (NGC 1569 and NGC 4214) with NGC 1569 showing a low-frequency extension of more than an arcmin beyond that detected in an archival 1.4 GHz radio image from WSRT. In the remaining two dwarf galaxies (NGC 2366 and DDO 50), the radio continuum emission appears clumpy with emission from H II regions dominating the integrated flux density. Assuming energy equipartition, we estimated the total magnetic field strength in NGC 4214 and NGC 1569. The mean magnetic field strength in NGC 4214 is about 11.5 μG. In the case of NGC 1569, the mean magnetic field in the inner galaxy is about 32 μG and falls down to 16 μG in the halo. The estimated field strengths are significantly stronger than the typical field strengths observed towards normal spiral galaxies. Since the sample of four galaxies studied here was selected based on their radio brightness, we argued in **chapter 4** that the upcoming LOFAR Two-metre Sky Survey (LoTSS; Shimwell et al. 2017) will not be sensitive enough to map the diffuse radio halos in a large number of nearby dwarf galaxies.

While the individual galaxies studied in chapters 2, 3, and 4 are all unique in their own way, four galaxies (NGC 4258, M 101, NGC 1569, and NGC 4214) show an interesting common feature: the angular extent of these four galaxies increases with decreasing frequency. We also find that the spectral index distribution in the outer parts of all four galaxies is steeper than their inner regions which suggests a dominance of old electrons in the outer parts of galaxies. In the outer parts of all four galaxies detected in our LOFAR images, we find weak magnetic fields with equipartition field strengths of the order of a few microGauss. The results presented in this thesis, along with recent low-frequency observations of other nearby spiral galaxies like M 51 (Mulcahy et al. 2014) and IC 10 (Heesen et al. 2018), paint a consistent picture that low-energy cosmic ray electrons (with long synchrotron lifetime) can propagate to large radii resulting in a systematic increase in the angular sizes of galaxies towards low radio frequencies. Thus, we can conclude that sensitive, low-frequency observations of nearby galaxies are an excellent tracer to study magnetic fields in the outer parts of galactic disks and halos of nearby galaxies.

Finally, in the era of data-intensive radio astronomy, a number of image processing algorithms can be sped up using new computational tools like General Purpose Graphical Processing Units (GPGPUs) to cope with the increasing data rates. In **chapter 5**, we have demonstrated a clear example of this by implementing a commonly used algorithm in radio polarimetry called Faraday Rotation Measure (RM) synthesis to work with GPGPUs thereby achieving a high compute throughput compared to existing CPU implementations of the same algorithm. Additionally, we have also demonstrated that the format in which the astronomical data is stored can have a significant impact on the performance of the algorithm. In the case of RM synthesis, we noticed that adopting the Hierarchical Data Format (HDF5) instead of the standard FITS format results in a significant decrease in the code execution time.

6.2 Avenues for future research

6.2.1 Broadband polarimetry as a probe of anomalous arms in NGC 4258

Recall from **chapter 2** that since the discovery of the anomalous arms in NGC 4258, numerous models have been proposed to explain the orientation of the arms with respect to the galactic disk. All the proposed models for the arms can be classified in two categories: *in-disk* and *out-of-disk* models. Both model categories are based on the assumption that the anomalous arms are produced by the interaction of matter ejected from the nucleus with either the gas in the disk (in-disk model) or with coronal gas in the halo (out-of-disk model). The 1.4 GHz radio polarimetry data presented in **chapter 2**, complemented by H I and Hα data suggests that the anomalous arms have a hybrid morphology where the outer parts of the eastern arm are located in front the galactic disk (on the near side to the observer) while the rest is embedded in the galactic disk.

While the polarization results presented in **chapter 2** favour a hybrid model for the anomalous arms, the results derived from our WSRT polarimetry data are only qualitative and the limited bandwidth of the WSRT data prevents us from performing any quantitative analysis such as comparing the observed Faraday depth along the anomalous arms with predicted Faraday depth distributions for different *in-disk* and *out-of-disk* models. Furthermore, we suggested that mapping the Faraday depth distribution along the anomalous arms could pinpoint the exact location where the eastern arm exits the disk. In order to carry out a quantitative analysis of the morphology of the anomalous arms using broadband polarimetry data, we have proposed to observe NGC 4258 in the L- and S-band covering the frequency range 1 – 4 GHz using the Karl G. Jansky Very Large Array.

6.2.2 Mapping the halos of nearby dwarf galaxies

Winds and outflows from galaxies play a vital role in shaping the evolutionary histories of galaxies. The energy and momentum from star formation that drives the outflows can enhance turbulence in the ISM which provides pressure balance to the gas in the ISM. The additional pressure generated in the ISM can balance gravity and hence impede further star formation. Additionally, outflows can remove gas and metals from the ISM and drive them out into the halo or into the circum-galactic medium if the outflow velocity is greater than the escape velocity of the galaxy. For a review of winds and outflows in galaxies, see Veilleux et al. (2005). On the other hand, if the outflow velocity is lower than the escape velocity of the galaxy, the hot gas driven by the outflow can provide a seeding mechanism to cool the hot coronal gas present in the halos of galaxies. The cool gas produced in this process can then rain down on the disk providing fuel for subsequent star formation in the galaxy through a mechanism called galactic fountains (Sancisi et al. 2008; Marinacci et al. 2010).

Dwarf galaxies are subject to strong outflows having only weak gravitational potentials and bursty star formation histories. Cosmic rays have long been suspected to play a vital role in driving these outflows. Hydrodynamic simulations of cosmic ray driven galactic winds by Uhlig et al. (2012) predict that dwarf galaxies with such an outflow should possess a large-scale spherically symmetric radio halo produced by cosmic ray electrons accelerating in the galactic magnetic field.

In addition to driving outflows in galaxies, cosmic rays also play a vital role in regulating the evolution of large-scale ordered magnetic fields in galaxies. Both simulations and radio polarimetric observations of superbubbles in nearby spiral galaxies indicate that starburst-driven galactic outflows can transport the ordered magnetic field lines from the inner regions of galaxies to the outer halo (see for example Brandenburg et al. 1995; Chyży et al. 2011; Heald 2012). Thus, studying outflows in dwarf galaxies can provide vital information not only about the winds and outflows but also about the evolution of large-scale magnetic fields in such systems. However, strong observational evidence for such a cosmic ray-driven outflow has been hard to come by due to (i) lack of sensitive radio observations to detect weak radio emission from the halos of dwarf galaxies, and (ii) lack of tools necessary to model different types of cosmic ray propagation.

Until recently, sensitive radio continuum searches for diffuse radio halos around nearby dwarf galaxies at GHz frequencies had failed to detect any synchrotron emission. However, our recent LOFAR HBA observations of the nearby dwarf galaxy NGC 1569 presented in **chapter 4** and our unpublished HBA observations of the dwarf galaxy NGC 4449 show that LOFAR is sensitive enough to map the weak, diffuse radio continuum emission from the halos that had evaded detection in previous higher frequency radio continuum observations. Furthermore, recent developments in software modelling of the 1D cosmic ray transport process in the radio halos of galaxies (see for example Heesen et al. 2016) allow us to differentiate between advective and diffusive winds in the halos of galaxies, as well as measure their wind speed. Thus, combining the power of LOFAR in detecting diffuse radio emission from the halos of a large sample of nearby dwarfs along with modelling the advective/diffuse outflows in the halos of these galaxies will provide important insights into the role of cosmic rays in driving outflows in dwarf galaxies.